Article:

Dürrenfeld, Philipp, Xu, Yongbing orcid.org/0000-0002-7823-0725, Åkerman, Johan et al. (1 more author) (2017) Controlled skyrmion nucleation in extended magnetic layers using a nanocontact geometry. Physical Review B. 054430. ISSN 2469-9969

https://doi.org/10.1103/PhysRevB.96.054430

Controlled Skyrmion nucleation in extended magnetic layers using a nano-contact geometry

Philipp Dürrenfeld,[1] Yongbing Xu,[1] Johan Åkerman,[2,3] and Yan Zhou[4]

[1] *School of Electronic Science and Engineering, Nanjing University, 210093 Nanjing, China*

[2] *Department of Physics, University of Gothenburg, 412 96 Gothenburg, Sweden*

[3] *Materials and Nanophysics, School of ICT, KTH Royal Institute of Technology, Electrum 229, 164 40 Kista, Sweden*

[4] *School of Science and Engineering, The Chinese University of Hong Kong, 518172 Shenzhen, China*

We propose and numerically simulate a spintronic device layout consisting of a nanocontact on top of an extended Co/Pt bilayer. The interfacial Dzyaloshinskii-Moriya interaction in such bilayer systems can lead to the possible existence of meta-stable Skyrmions. A current injected through the nanocontact enables the manipulation of the Skyrmion size, the annihilation, and controlled nucleation of single Skyrmions with ps-long pulses. The results are obtained from micromagnetic simulations and can be potentially used for future magnetic storage implementations.

Skyrmions in ultrathin perpendicularly magnetized films with Dzyaloshinskii-Moriya interaction (DMI) are a future candidate for magnetic information storage due to their intrinsic nanoscaled dimensions.[1,2] Controllable writing of single Skyrmions is therefore crucial for applications. Writing schemes have been studied that rely on the presence of an additional polarizing layer[3–6] or a domain wall,[7,8] leading to generally complex implementations. Recently, the generation of Skyrmions aided by spin Hall effect induced non-uniform torques in a simplified ferromagnetic metal (FM)/heavy non-magnetic metal layer structure was shown, however, lacking the controllability of writing single Skyrmions.[9] The heavy metal layer in this bilayer layout provides both the interfacial DMI as well as the spin Hall effect[10,11] to induce pure spin currents into the ferromagnet. These spin Hall effect torques in FM/heavy metal bilayers are otherwise frequently used in spin Hall nano-oscillators.[12–16] Recent studies also show that the implementation of DMI into such spin Hall nano-oscillators[17] or the use of Skyrmions in spin torque oscillators[18] are promising for communication applications.

Here we propose a scheme, in which current injected into a nanocontact (NC) on top of a Co/Pt bilayer results in a spatially non-uniform spin torque, allowing for the manipulation of the Skyrmion size, the annihilation, and the controlled nucleation of single Skyrmions in an extended magnetic layer.

As a model system for the simulations serves a bilayer of Co (0.8 nm)/Pt (3 nm). Firstly, the current distribution and Oersted field in a bilayer disk of 1024 nm diameter with a centrally located NC of 30 nm diameter is calculated through a 3D model using the COMSOL Multiphysics® modeling software. The assumed specific resistivities were $\rho_{\mathrm{Pt}} = 12\times10^{-8}$ Ωm and $\rho_{\mathrm{Co}} = 40\times10^{-8}$ Ωm.[19,20] The calculated electrical current density J_{e} in the Platinum layer, near the Pt/Co interface, is plotted in Fig. 1 for a current of 1 mA with the highest current densities being reached at the perimeter of the nanocontact. In the proposed layout and in the

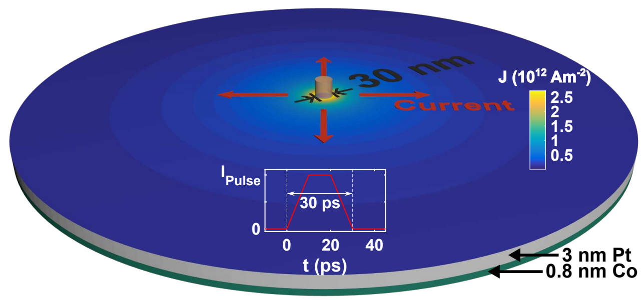

Figure 1. (color online) Schematics of the simulated layout with a 30 nm diameter NC and current flowing radially away from it. Color represents the in-plane current density in the Pt layer. Inset: 30 ps current pulses are used to write single Skyrmions underneath the NC.

following micromagnetic simulations, only the in-plane components of the current in Pt are taken into account, as the calculations show that the vertical current flow underneath the nanocontact is negligible.

The current flowing radially away from the NC leads to a spin accumulation at the Pt/Co interface due to the spin Hall effect, resulting in a spin current into the Co layer. The ratio of the spin current density J_{s} to J_{e} is given by the spin Hall angle of Pt, which we assume to be 0.08 in our micromagnetic simulations, a value previously determined for similar Pt/FM bilayer systems.[21,22] The polarization of the such calculated spin current is consequently set to 1 in our micromagnetic simulations. However, the direction of the accumulated spins and therefore the polarization orientation of the spin current is non-uniform as they are oriented 90° away from the local in-plane current direction and thus are arranged similarly to a vortex. Overall, the implementation of the non-uniform spin torque from the spin Hall effect in our simulations is done in a similar way as it was successfully used for the micromagnetic description of spin Hall nano-oscillators.[15,22–24]

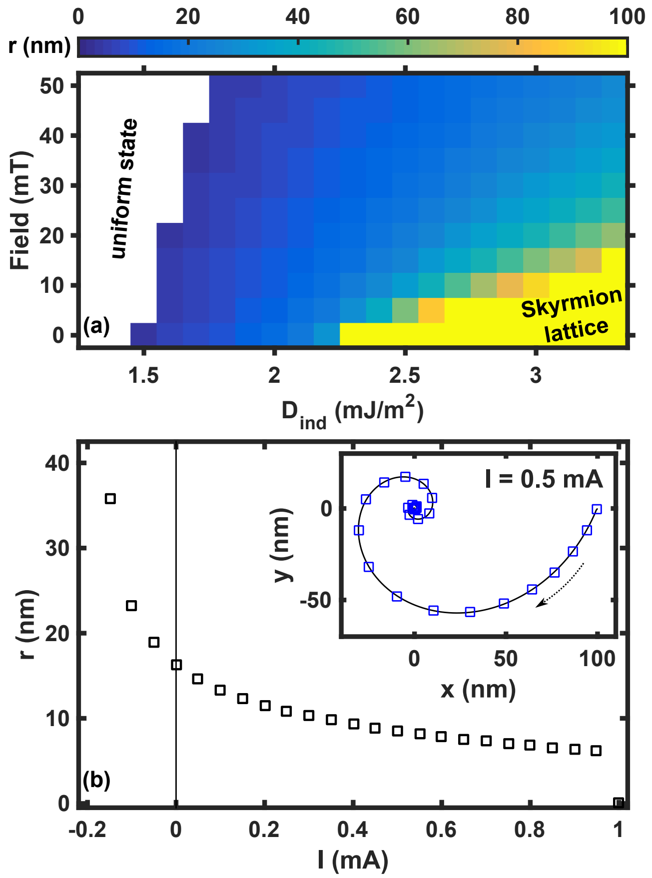

Figure 2. (color online) (a) Skyrmion radius as a function of an applied perpendicular field and DMI strength. (b) Radius of a Skyrmion placed underneath the NC ($D_{\mathrm{ind}} = 2$ mJ/m^2 and zero field) and subjected to a small current. Inset: Trajectroy of a Skyrmion in the vicinity of the NC that gets attracted by a current of 0.5 mA. The blue squares are placed in time intervals of 1 ns.

The micromagnetic simulations were done using the graphics processor unit (GPU)-based finite-difference micromagnetic solver MuMax3.[25] For these the free layer is discretized into a 1024 × 1024 × 1 grid, resulting in a cell size of 1 nm × 1 nm × 0.8 nm. The parameters of the Co layer are saturation magnetization $M_{\mathrm{S}} = 1.31\times10^6$ A/m, exchange stiffness $A = 22$ pJ/m, Gilbert damping $\alpha = 0.3$, and an out-of-plane anisotropy energy density of $K_{\perp} = 1.28\times10^6$ J/m^3, all values extracted from Ref. 26. The Oersted field is rather small, yet included in the simulations. The simulations are performed for the temperature $T = 0$ K, unless otherwise noted.

The influence of an interfacial Dzyaloshinskii-Moriya strength D_{ind} and a small perpendicular magnetic field on the size of a Skyrmion placed in the center of the simulation area are plotted in Fig. 2(a). For a too small D_{ind}<1.5 mJ/m^2 the system will always relax into a uniform out-of-plane magnetized state and for a too large D_{ind} the system tends to relax into a Skyrmion with a size similar to the simulation area or even multiple Skyrmions. In our study, we focus on the situation of isolated Skyrmions, *i.e.*, where a relaxed Skyrmion has a size much smaller than the simulation area. As it is shown in Fig. 2(a), such a state can be experimentally achieved for a large range of D_{ind} with the application of a perpendicular magnetic field.

In a first step, we study the effect of a small current through the NC on the Skymrion size, which is plotted for zero field and $D_{\mathrm{ind}} = 2$ mJ/m^2 in Fig. 2(b). The current is hereby switched on instantly after the Skyrmion has fully relaxed (0.5 ns). The new Skyrmion size is typically reached within less than 2 ns and decreases (increases) for positive (negative) currents. For currents ≥1 mA, the initial Skyrmion is annihilated and thus the broken symmetry in our model system enables us to delete a single Skyrmion, which is placed underneath the NC.

Experimentally it will be almost impossible to place an already existing Skyrmion, *e.g.*, with a uniform in-plane current, exactly underneath the NC. However, in our geometry a small positive current also leads to a trapping of a nearby Skyrmion due to the motion from the Skyrmion Hall effect.[27] This is exemplarily shown in the inset of Fig. 2(b) for a current of 0.5 mA and a Skyrmion initially placed 100 nm away from the center of the NC ($x = y = 0$). One could also apply larger positive currents and thus speed up this trapping process, if the final aim was the annihilation of the Skyrmion.

Next, we discuss the case of an initially uniformly magnetized film, where a larger current is applied as a 30 ps long pulse, which leads to the controlled nucleation of a Skymrion underneath the NC. The pulse consists of 10 ps each rising time, constant current, and falling time, see inset of Fig. 1, and is chosen solely to resemble an experimentally achievable pulse generator output. The following results do not rely on its exact shape and could be reproduced with, *e.g.*, a 20 ps rectangular pulse. The case of zero applied field, $D_{\mathrm{ind}} = 2$ mJ/m^2, and a current pulse of -22 mA is depicted in Figs. 3(a)-(g). The spin transfer torque hereby leads to a temporary tilting of the magnetization into the film plane immediately around the perimeter of the NC, Fig. 3(b), which then relaxes into a ring-like domain state, Fig. 3(c). In this state the magnetization configurations at the outer and inner boundary of the reversed ring-shaped domain have a chirality, leading to a non-zero topological charge density. The topological charge density has reversed signs at both boundaries, and thus the Skyrmion number S still sums up to 0 over the whole area. However, while the system relaxes further, the ring-shaped area of reversed magnetization shrinks by moving both boundaries inwards. This eventually leads to the case where the inner area becomes infinitely small, Fig. 3(d). Despite the topological charge of the inner area, it finally annihilates, Fig. 3(e), and reverses its magnetization to give way to a further exchange energy minimization of the system. At this point, the resulting Skyrmion number becomes 1 and the magnetization finally relaxes to the (meta-)stable

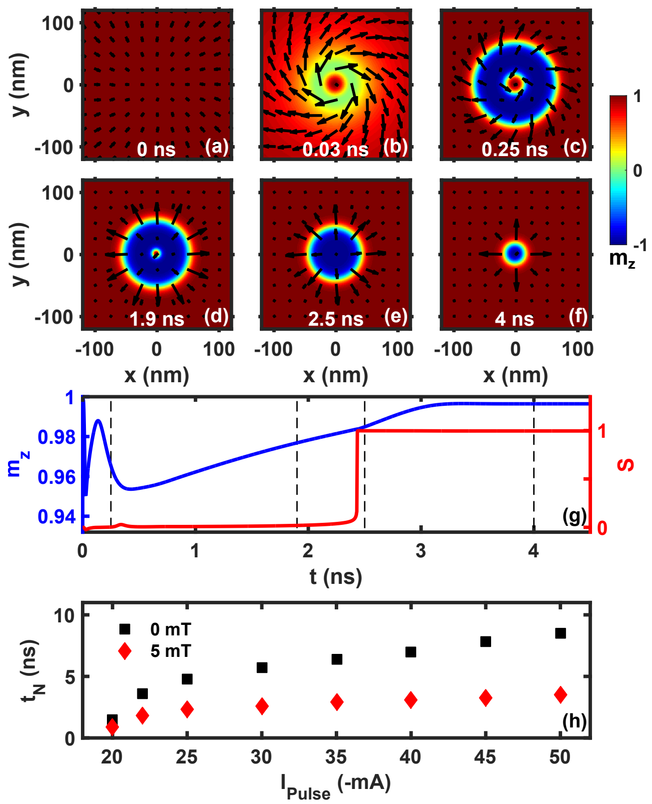

Figure 3. (color online). Skyrmion nucleation with a current pulse of -22 mA. (a)-(f) Time snapshots of the nucleation process. Color denotes the z-component of the normalized magnetization (m_Z) and the arrows relate to the in-plane direction of the magnetization. (g) Plot of averaged m_Z and S as a function of time. The current pulse is applied between 0 and 0.03 ns. The dashed lines mark the times of (c)-(f). (h) Nucleation time until fully relaxed Skyrmion as a function of the current pulse amplitude for zero field and 5 mT.

state of a single Skyrmion, Fig. 3(f).

The time needed for this process — until the stable Skyrmion radius is reached — as a function of the current pulse amplitude is plotted in Fig. 3(h) and shows a monotonic increase with a threshold current of -20 mA. A larger current results in a larger ring-shaped domain structure, which in-turn takes more time to relax. Positive current pulses of similar amplitudes do not result in the nucleation of a Skyrmion. In the case of zero field, only the exchange energy minimization at the domain boundaries drives the above described process after the pulse application. However, already the introduction of an additional 5 mT perpendicular field and its accompanying Zeeman energy promotes the shrinkage of the reversely magnetized ring domain, resulting in a significantly faster relaxation process.

The transportation of a such generated Skyrmion in a prospective magnetic storage application could be achieved by uniform in-plane currents. Assuming this possibility of controlled placement either on a straight line or even freely in two dimensions, it is important that

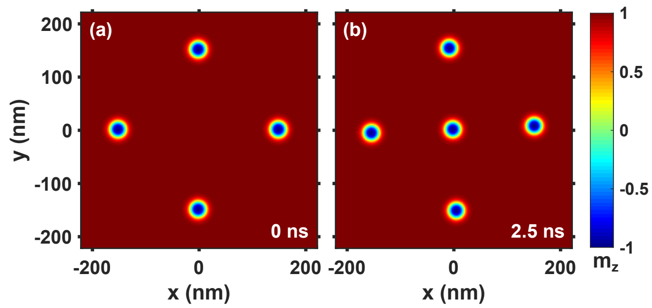

Figure 4. (color online). Writing of an additional Skyrmion into an already present structure with four Skyrmions initially placed 150 nm away from the NC. I_{pulse} = -22 mA, D_{ind} = 2 mJ/m^2, and an out-of-plane field of 5 mT are used.

newly generated Skyrmions are not affected by neighboring ones and vice versa. In Fig. 4 we show a simulation, where four Skyrmions are placed initially each 150 nm away from the NC. The current pulse amplitude is -22 mA and an out-of-plane field of 5 mT is applied to decrease the nucleation time. Except the occurence of the central new Skyrmion, it can be seen that the initial ones have been slightly rotated counter-clockwise (∼7 nm) around and pushed away (∼2 nm) from the NC. This is a result of the Skyrmion Hall effect, which was similarly used earlier for the trapping of a nearby Skyrmion. This misplacement naturally increases for larger or longer current pulses as well as for Skyrmions that are initially placed closer to the NC. In case they are placed too close to the NC, ∼50 nm for the conditions simulated here, no additional Skyrmion is nucleated and they rather merge with the initial ones.

Due to both the increasing influence of nucleation on neighboring Skyrmions and the increasing nucleation time, the threshold current pulse amplitude can be considered as the ideal point for prospective applications.

As mentioned earlier, the findings of the controlled nucleation of a single Skyrmion are robust against changes in the exact current pulse shape. Moreover, the same results have been obtained with different simulation grids (1536 × 1536 × 1 and 768 × 768 × 1) as well as a NC placed slightly off-center ($x \neq y \neq 0$), both to exclude simulation artifacts. The size of the NC can be also varied, even down to a theoretical diameter of 0, without changing the results of the paper. The inclusion of a finite temperature T = 300 K in the simulations leads to changes in the state diagram of the Skyrmions, such that generally lower values of D_{ind} are required for single isolated Skyrmions. However, after adjusting for this change, *i.e.*, D_{ind} = 1.5 mJ/m^2 instead of 2 mJ/m^2 for the simulations shown above, the annihilation and nucleation mechanisms of a Skyrmion underneath the NC are restored.

In summary, we have proposed and simulated a structure based on a NC placed on top of an extended bilayer film, where the DMI in the ultrathin Co is provided by a Pt layer, which also serves as a source of pure spin currents due to the spin Hall effect. In such a layout, individual Skyrmions are nucleated by negative polarity current pulses and annihilated by small positive currents.

Support from the Swedish Foundation for Strategic Research (SSF), the Swedish Research Council (VR), and the Knut and Alice Wallenberg Foundation is gratefully acknowledged. J. Å. is a Royal Swedish Academy of Sciences Research Fellow supported by a grant from the Knut and Alice Wallenberg Foundation.

REFERENCES

[1] R. Wiesendanger, Nat. Rev. Mater. **1**, 16044 (2016).
[2] W. Kang, Y. Huang, X. Zhang, Y. Zhou, and W. Zhao, Proc. IEEE **104**, 2040 (2016).
[3] N. Romming, C. Hanneken, M. Menzel, J. E. Bickel, B. Wolter, K. von Bergmann, A. Kubetzka, and R. Wiesendanger, Science **341**, 636 (2013).
[4] J. Sampaio, V. Cros, S. Rohart, A. Thiaville, and A. Fert, Nat. Nanotechnol. **8**, 839 (2013).
[5] X. Zhang, Y. Zhou, and M. Ezawa, Nat. Commun. **7**, 10293 (2016).
[6] H. Y. Yuan and X. R. Wang, Sci. Rep. **6**, 22638 (2016).
[7] Y. Zhou and M. Ezawa, Nat. Commun. **5**, 4652 (2014).
[8] X. Zhang, M. Ezawa, and Y. Zhou, Sci. Rep. **5**, 9400 (2015).
[9] W. Jiang, P. Upadhyaya, W. Zhang, G. Yu, M. B. Jungfleisch, F. Y. Fradin, J. E. Pearson, Y. Tserkovnyak, K. L. Wang, O. Heinonen, S. G. E. te Velthuis, and A. Hoffmann, Science **349**, 283 (2015).
[10] J. E. Hirsch, Phys. Rev. Lett. **83**, 1834 (1999).
[11] J. Sinova, S. O. Valenzuela, J. Wunderlich, C. H. Back, and T. Jungwirth, Rev. Mod. Phys. **87**, 1213 (2015).
[12] V. E. Demidov, S. Urazhdin, H. Ulrichs, V. Tiberkevich, A. Slavin, D. Baither, G. Schmitz, and S. O. Demokritov, Nat. Mater. **11**, 1028 (2012).
[13] L. Liu, C.-F. Pai, D. C. Ralph, and R. A. Buhrman, Phys. Rev. Lett. **109**, 186602 (2012).
[14] M. Ranjbar, P. Dürrenfeld, M. Haidar, E. Iacocca, M. Balinskiy, T. Le, M. Fazlali, A. Houshang, A. Awad, R. Dumas, and J. Åkerman, IEEE Magn. Lett. **5**, 3000504 (2014).
[15] A. A. Awad, P. Dürrenfeld, A. Houshang, M. Dvornik, E. Iacocca, R. K. Dumas, and J. Åkerman, Nat. Phys. , doi: 10.1038/nphys3927 (2016).
[16] H. Mazraati, S. Chung, A. Houshang, M. Dvornik, L. Piazza, F. Qejvanaj, S. Jiang, T. Q. Le, J. Weissenrieder, and J. Åkerman, Appl. Phys. Lett. **109**, 242402 (2016).
[17] A. Giordano, R. Verba, R. Zivieri, A. Laudani, V. Puliafito, G. Gubbiotti, R. Tomasello, G. Siracusano, B. Azzerboni, M. Carpentieri, A. Slavin, and G. Finocchio, Sci. Rep. **6**, 36020 (2016).
[18] F. Garcia Sanchez, J. Sampaio, N. Reyren, V. Cros, and J.-V. Kim, New J. Phys. **18**, 075011 (2016).
[19] H. Ulrichs, V. E. Demidov, S. O. Demokritov, W. L. Lim, J. Melander, N. Ebrahim Zadeh, and S. Urazhdin, Appl. Phys. Lett. **102**, 132402 (2013).
[20] M. Li, Y.-P. Zhao, and G.-C. Wang, J. Vac. Sci. Technol. A **18**, 2992 (2000).
[21] L. Liu, T. Moriyama, D. C. Ralph, and R. A. Buhrman, Phys. Rev. Lett. **106**, 036601 (2011).
[22] A. Giordano, M. Carpentieri, A. Laudani, G. Gubbiotti, B. Azzerboni, and G. Finocchio, Appl. Phys. Lett. **105**, 042412 (2014).
[23] H. Ulrichs, V. E. Demidov, and S. O. Demokritov, Appl. Phys. Lett. **104**, 042407 (2014).
[24] T. Kendziorczyk and T. Kuhn, Phys. Rev. B **93**, 134413 (2016).
[25] A. Vansteenkiste, J. Leliaert, M. Dvornik, M. Helsen, F. Garcia Sanchez, and B. Van Waeyenberge, AIP Adv. **4**, 107133 (2014).
[26] P. J. Metaxas, J. P. Jamet, A. Mougin, M. Cormier, J. Ferré, V. Baltz, B. Rodmacq, B. Dieny, and R. L. Stamps, Phys. Rev. Lett. **99**, 217208 (2007).
[27] W. Jiang, X. Zhang, G. Yu, W. Zhang, X. Wang, M. Benjamin Jungfleisch, J. E. Pearson, X. Cheng, O. Heinonen, K. L. Wang, Y. Zhou, A. Hoffmann, and S. G. E. te Velthuis, Nat. Phys. , doi: 10.1038/nphys3883 (2016).